# MAPPING EVAPOTRANSPIRATION USING
# LANDSAT AND THE METRIC EVAPOTRANSPIRATION MODEL

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## ABSTRACT

From 2000 to 2005, the Idaho Department of Water Resources and the University of Idaho used a NASA Synergy grant to develop an evapotranspiration model that uses Landsat TM data as the primary input. The METRIC evapotranspiration model computes a complete energy balance for each pixel from any satellite with visible, near infrared, and thermal infrared bands. Evapotranspiration is a component of the energy balance. The University of Idaho developed the METRIC model by modifying the European evapotranspiration model, SEBAL. The most significant modification is the incorporation of reference evapotranspiration as computed by the U.S. Bureau of Reclamation's system of AgriMet stations. The Idaho Department of Water Resources developed applications for METRIC in water planning, water rights monitoring, aquifer depletion, hydrologic modeling, water-use data, and water administration. The University of Idaho developed applications in California's Imperial Valley and in the Rio Grande Valley. Using Landsat data as input to the METRIC model has the advantages of a relatively small pixel size over large areal coverage at reasonable cost. Further, the archive of Landsat TM data allows mapping of evapotranspiration backwards in time for 20 years. The Idaho METRIC applications are one part of a rapidly expanding suite of world-wide applications for which the Landsat thermal band is critical.

## INTRODUCTION

METRIC (Mapping Evapotranspiration at high Resolution and with Internalized Calibration) is an image-processing tool for computing evapotranspiration (ET). In METRIC, ET is a residual of the energy balance at the earth's surface. METRIC is a variation of the SEBAL, which was developed in the Netherlands by Bastiaanssen (1998a, 1998b). Unlike SEBAL, METRIC uses ground-based, reference ET. Both METRIC and SEBAL use Landsat Thematic Mapper data as the primary source of input data.

Initial application and testing of METRIC shows substantial promise as an efficient, accurate, and relatively inexpensive procedure to map actual ET from irrigated lands throughout a growing season. ET from satellite images may replace current procedures that rely on ground-based ET equations and generalized crop coefficients.

The internal calibration of the sensible heat computation within METRIC eliminates the need for atmospheric correction of reflectance measurements using radiative transfer models (Tasumi et al., 2004), and means that absolute temperature is not needed.

METRIC has been applied in several parts of the United States, but the bulk of the applications have been in Idaho, where the Idaho Department of Water Resources (IDWR) and the University of Idaho (UI) have used METRIC to compute monthly and seasonal ET for a variety of applications in water planning and water rights administration. IDWR has used METRIC to 1) set water budgets for hydrologic modeling, 2) monitor compliance with water rights, 3) support water planning, 4) estimate aquifer depletion, and 5) estimate water use by irrigated agriculture (Allen, et al., 2005). UI has applied METRIC in other parts of the United States (Allen, et al., 2005).

## THEORY

Allen, et al. (2005) explain the theory behind METRIC in detail, but Figure 1 offers a concise illustration. ET is calculated as a residual of the surface energy equation

$$LE = R_n - G - H$$

where LE is the latent energy consumed by ET, $R_n$ is net radiation (sum of all incoming and outgoing shortwave and longwave radiation at the surface), G is sensible heat flux conducted into the ground, and H is sensible heat flux convected into the air. $R_n$ is computed from satellite-measured narrow-band reflectances and surface temperature; G is estimated from $R_n$, surface temperature, and a vegetation index; and H is estimated from surface temperature ranges, surface roughness, and wind speed using buoyancy corrections. The algorithms used in METRIC for $R_n$ and G stem from those used in early SEBAL applications by Bastiaanssen et al. (1998a).

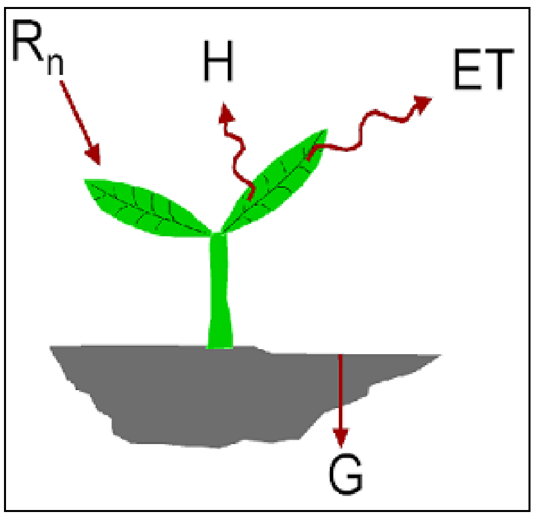


**Figure 1.** Diagram of the energy balance relationships that yield ET. $R_n$ is net radiation, H is sensible heat convected to the air, G is sensible heat convected to the ground, and ET is evapotranspiration.

## APPLICATIONS

IDWR developed five separate applications of the METRIC ET model. These applications use METRIC-derived ET to 1) set water budgets for hydrologic modeling, 2) monitor compliance with water rights, 3) compute ET by land use / land cover type, 4) compute aquifer depletion, and 5) compute water use by irrigated agriculture. UI applied METRIC to 1) examine ET patterns in agricultural fields, and 2) map ET from agriculture and riparian vegetation.

### Water Budgets for Hydrologic Modeling

The Lower Boise Valley in Idaho is receiving significant attention because of rapid population growth. Beginning in 1995, IDWR led a multi-agency team in the construction of a groundwater model of the valley. The U.S. Bureau of Reclamation spent three years studying irrigation diversions from the Boise River and irrigation return flow into the river in order to better quantify the water balance for the model. The third main component of the water balance is ET.

IDWR compared METRIC-derived ET and the ET used in the 1996 Water Budget. This preliminary comparison was made using three model cells within the Treasure Valley Hydrologic Project ground water model; the selected cells were those three having the greatest flood-irrigated acreage. Each model cell is 2.59 $km^2$ in area.

Table 1 is an example of the data used in the initial comparison. The weighted average ET used in the 1996 Water Budget was 737 mm. This value was calculated using the ET crop coefficients for the 11 crop types, the percentage of total cropped area for each crop, and the average $ET_r$ for the years 1988-1994 from the Parma Field Station. METRIC yielded more spatially variable ET values.

| Model Row | Model Column | Hectares Flood Irrigated | Water Budget ET Millimeters | METRIC ET (1997) Millimeters |
|---|---|---|---|---|
| | | | | Apr. 15 to Oct. 15 |
| 10 | 17 | 255 | 737 | 731 |
| 11 | 18 | 652 | 737 | 820 |
| 28 | 25 | 251 | 737 | 661 |

**Table 1**. A Comparison of METRIC ET with average ET for three cells of the Treasure Valley hydrologic model.

## Monitoring Water Rights Compliance

IDWR presently has the technical means to identify diversions not having a water right by overlaying water-right polygons onto map-registered Landsat false-color images. However, the technical means to identify someone using water "in excess of the elements or conditions of a water right" is more problematic.

IDWR tested METRIC as an operational regulatory tool for administering water rights. The test attempted to identify fields onto which water was applied in violation of the maximum rate of diversion of the water right. The test covered part of the Eastern Snake River Plain, an area in Landsat path-row 39/30, for the 17-day period between and including two Landsat overpass dates. The test compared righted pumpage rates with ET for water-right places-of-use during the period of peak water demand in July. The comparison was done for 426 water rights in the study area, and compared cumulative ET, as computed by METRIC for the 17 days, with the maximum possible volume of water authorized to be diverted onto a field based on valid water rights.

UI/Kimberly personnel processed two July 2002 Landsat scenes (July 12 and July 28) through METRIC and delivered the data to IDWR. IDWR compared the ET data for the 426 fields with water rights data. The entire analysis was completed in less than 2 weeks after the second overpass date. Authorized diversion volume was calculated based on the allocated rate of flow, continuously diverted over the 17-day period. The comparison results are presented in Figure 2 where water right volume is plotted on the horizontal axis and consumption on the vertical axis. The points lying above the diagonal line indicate consumption exceeding authorized diversions. The line of points at 206 mm on the y-axis is a function of the bounds put on water rights by Idaho Statute.

IDWR personnel compared 426 water rights with METRIC-generated ET, and 18 of those were found to have ET greater than the water right could provide. Those 18 water rights were handed-off to water-rights personnel for further research.

The enforcement process using METRIC offers a significant improvement over the present method that uses power records. METRIC data can be processed for analysis during the irrigation season, which allows enforcement actions to be brought in a timely manner. Analysis of power meter records generally cannot be accomplished during the irrigation season due to the reporting protocols and restrictions on personnel time.

## Evapotranspiration by Land Use/Land Cover Class

The purpose of this project was to compute the ET by land use/land cover (LULC) (Morse, et al., 2003). Water planners at IDWR need to understand how the demand for water will be affected during the next 50 years by the transition of land from irrigated agriculture to residential, commercial, and industrial LULC types. IDWR is responsible for comprehensive river basin planning in Idaho. One of the important issues the planners are contending with is the potential for water availability in a valley that is rapidly changing from agricultural land use to more urban types of land uses.

IDWR computed and mapped ET by LULC class. The U.S. Bureau of Reclamation and IDWR previously cooperated to generate an LULC classification of the Boise River Valley for the year 2000 from 1:24,000-scale aerial photographs. The classification consists of twenty-four LULC classes in a vector format.

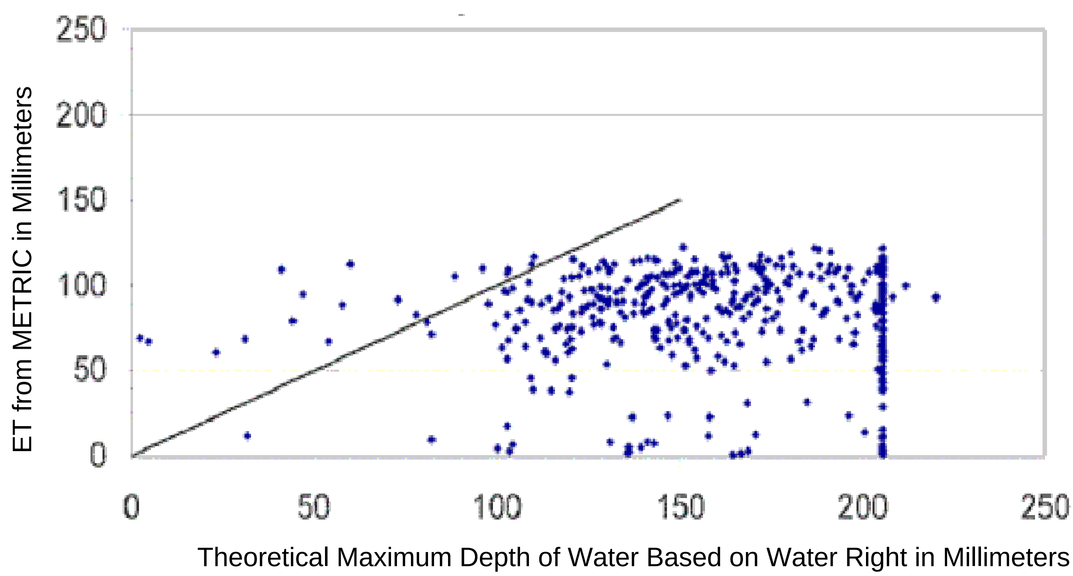


**Figure 2**. Comparison of cumulative METRIC ET with maximum water-right ET for 426 water right polygons in Idaho Department of Water Resources Basin 35 for July 12-July 28, 2002 period.

The aerial photographs were scanned to 1.5-meter pixels and registered to the Idaho Public Land Survey System base. The registered photographs were mosaicked into tiles that covered an area of approximately 93 square kilometers. IDWR personnel developed comprehensive descriptions of 24 LULC classes for the project. The descriptions were modified from MacConnell (1973) and are available in Kramber, et al., (1997).

For this analysis seven dates of Landsat data were processed through METRIC to develop seasonal ET for the period March 15 through October 15, 2000. The image dates are March 21, April 30, June 1, June 25, July 27, August 28, and October 2.

Figure 3a is a color infrared image of a portion of the lower Boise River Valley. Figure 3b is the corresponding area classified to land use and land cover. IDWR personnel overlaid the LULC polygons on the image of seasonal ET (Figure 3c) and computed the average seasonal ET for each class from all the polygons of each class. The result is summarized in Table 2, which shows the mean ET by LULC class with the associated standard deviation, and the total area of each class.

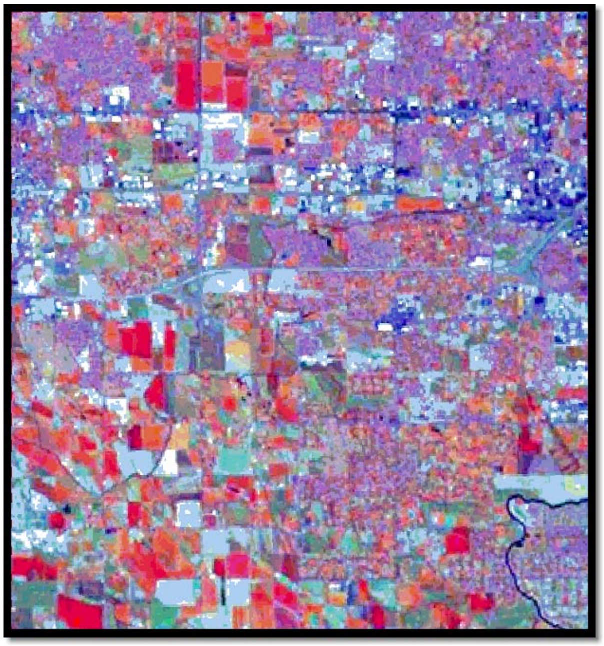

**Figure 3a**. FCC image of T3NR1E of the Boise Valley.

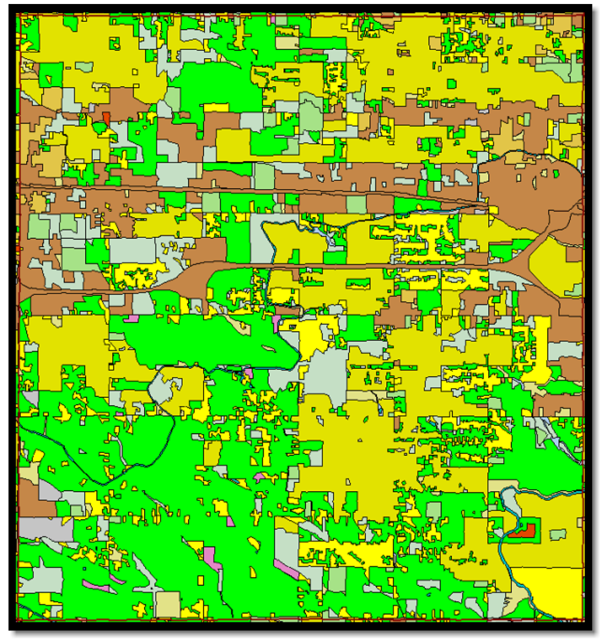

**Figure 3b**. Land use/land cover polygons in T3NR1E of the Boise Valley.

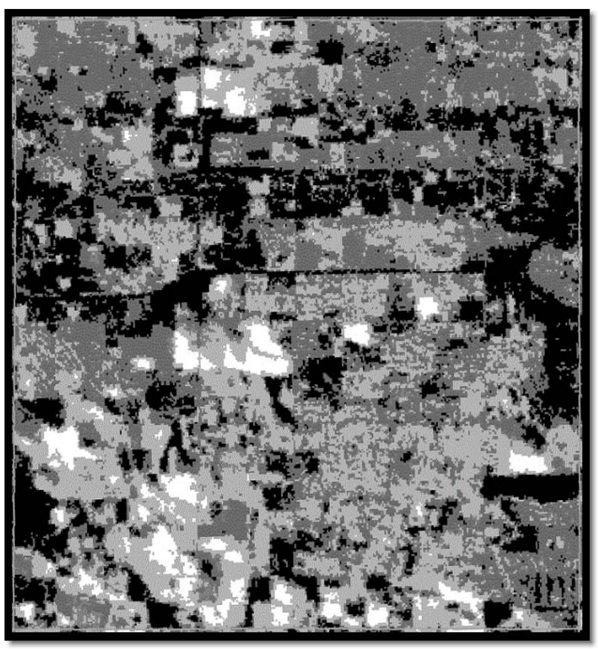

**Figure 3c**. ET image of T3NR1E the Boise Valley.

| Class Name | Seasonal ET in mm | Standard Deviation | Area in hectares |
|---|---|---|---|
| Wetland | 1,025 | 285 | 5,862 |
| Water | 924 | 165 | 5,344 |
| Recreation | 826 | 252 | 2,057 |
| Perennial | 820 | 212 | 2,711 |
| Irrigated Crops | 812 | 189 | 141,075 |
| Canal | 731 | 203 | 2,745 |
| Urban Residential | 684 | 157 | 4,126 |
| Rural Residential | 657 | 192 | 10,164 |
| Farmstead | 609 | 188 | 2,243 |
| New Subdivision | 606 | 146 | 11,516 |
| Sewage | 552 | 256 | 232 |
| Public | 548 | 263 | 2,120 |
| Other Agriculture | 536 | 243 | 2,853 |
| Dairy | 524 | 182 | 604 |
| Feedlot | 479 | 205 | 1,691 |
| Junk Yard | 467 | 193 | 129 |
| Abandoned Agriculture | 459 | 211 | 1,837 |
| Transition | 437 | 195 | 2,712 |
| Idle Agriculture | 436 | 215 | 3,042 |
| Transportation | 420 | 222 | 2,313 |
| Commercial and Industrial | 380 | 196 | 5,762 |
| Barren | 335 | 258 | 1,912 |
| Unclassified | 298 | 239 | 12,742 |
| Rangeland | 242 | 160 | 90,647 |
| Petroleum Tanks | 237 | 112 | 18 |

**Table 2**. Mean seasonal ET by land use/land cover class

## Aquifer Depletion

The relationship between ET and ground water pumpage is important for IDWR regulatory processes. Historically, surface water diversions have been closely monitored while ground water diversions have not. Approximately 300 monitored diversions from the Snake River irrigate approximately 647,500 hectares on the Eastern Snake River Plain (ESRP). The ESRP also supports approximately 200,000 hectares of ground water irrigation from approximately 6,000 wells. From a logistical point alone, monitoring ground water pumpage is a large undertaking.

IDWR and other, associated organizations presently spend approximately $500,000 per year on monitoring ground water pumpage from the ESRP. The Water Distribution Section of IDWR has visited the 6,000 wells on the ESRP over the last 5 years to record the GPS location and to measure the well flow and simultaneous power consumption. These data are stored in the Water Management Information System, which is used to estimate ground water pumpage using the power-meter records for its constituent wells.

This application hypothesizes that there is a correlation between METRIC ET and ground water pumpage, and that for a given water right, the ET for the field or fields covered by that water right can be used to estimate the volume of water pumped from the corresponding well.

The comparison between METRIC ET and pumpage used 184 field-well combinations. Figure 4 shows the scatter plot of the two variables. No clear relationship is obvious, and a first-order polynomial regression confirms the lack of correlation with an $r^2 = 0.14$. Nevertheless, a close examination of the two data sets is revealing.

Figures 5a and 5b show the scatter within each individual variable of the dataset plotted with AgriMet ET data. The AgriMet data show the ET extremes of alfalfa and peas, and were recorded for the year 2000 at the U.S. Bureau of Reclamation AgiMet station in Aberdeen, Idaho. The Aberdeen Station is within approximately 32 km. of these fields, and is representative of them.

The two plots reveal useful information. In Figure 5a, nearly all the METRIC ET observations fall between the extremes of ET, which is the lowest at 365 mm for peas and highest at 890 mm for alfalfa. Further, there is a distinct “floor” at approximately 600 mm of ET, which is an indication of a practical minimum level of ET from irrigated agriculture. Most of the data fall well above peas, the local crop that uses the least water.

Contrast the METRIC ET pattern of Figure 5a with the pattern for pumpage as illustrated by Figure 5b. The pumpage data are not consistent at either the high end of the chart or at the low end. There is no “floor” evident to show that there is a minimum level of pumping needed to support an irrigated crop. In fact, the pumpage data set indicate that some fields are getting no water at all. The reliability of the dataset is called into question by the lack of patterns that reflect irrigation practice on the ESRP, and by the abundance of data at the extreme low end of the chart.

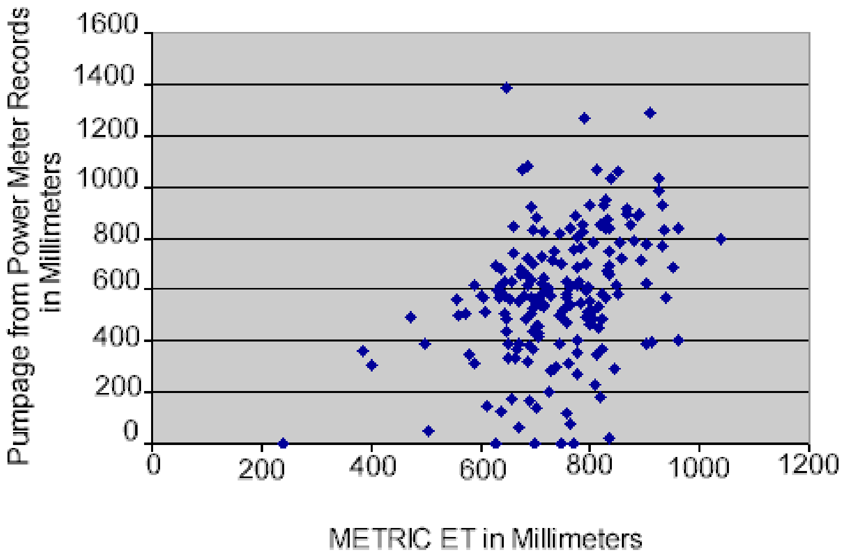


**Figure 4**. The scatter plot of pumpage versus METRIC ET in millimeters for the period April – October, 2000.

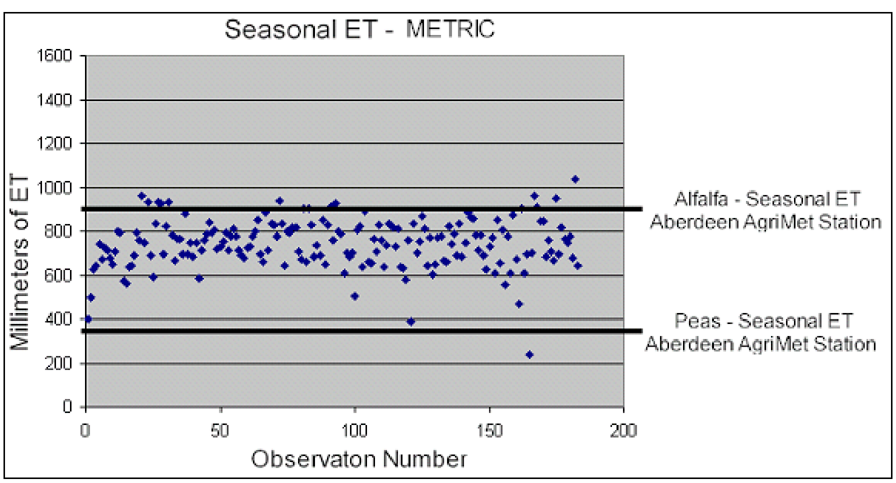


**Figure 5a**. April to October, 2000 METRIC ET compared with AgriMet ET extremes.

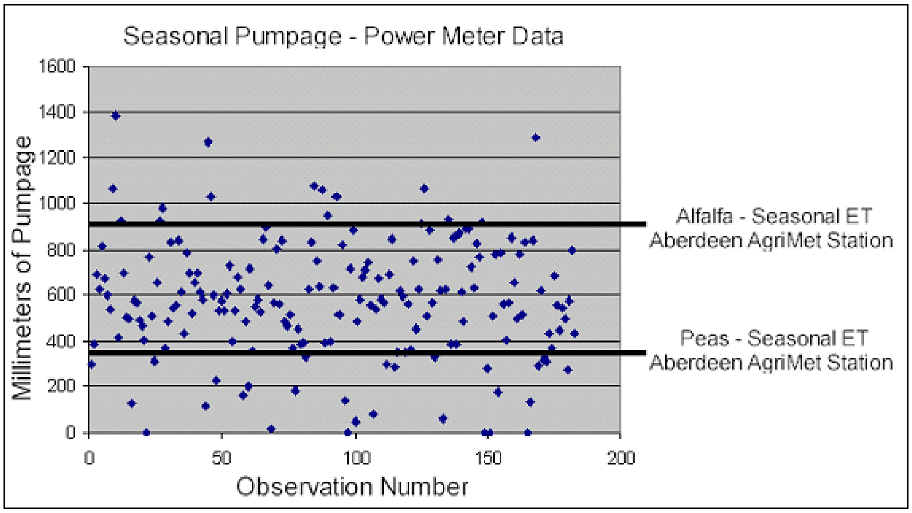


**Figure 5b**. April to October, 2000 pumpage compared with AgriMet ET extremes.

## Water Use by Irrigated Agriculture

In 1995, the U.S. Geological Survey estimated consumptive water use by irrigated agriculture accounted for more than 99% of total water use in Idaho (Solley, et al., 1998). The most recent water-use estimate was done for the year 2000. Unlike previous years, USGS did not report water use by irrigated agriculture (Hutson, et al., 2004). The value of Idaho's irrigated agriculture was $2.58 billion in 1997. The Idaho Department of Water Resources wanted water use statistics for 2000, but knew the process would be expensive and time-consuming. Landsat data processed through METRIC offered an alternative solution (Morse, et al., 2004).

Landsats 7 and 5 were used for this application, with multiple dates processed for nine nominal scenes for the year 2000 in 28 counties of southern Idaho, the region of the state where irrigated agriculture is concentrated. Land in irrigated agriculture was delineated using National Land Cover Data, other data, and thresholding of evapotranspiration values. METRIC computed 9,313,503 acre feet of evapotranspiration from 3,552,174 irrigated acres, or 2.6 acre feet per acre. The irrigated acreage is biased high due to the generalizing affect of the land use/land cover data set. Nevertheless, the results suggest that past water use data may have under estimated consumptive use.

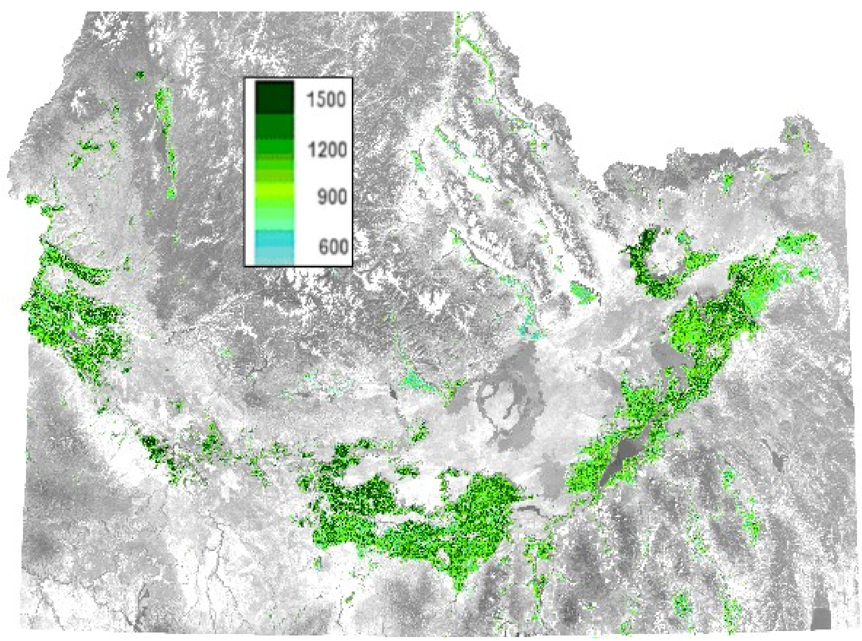


**Figure 6.** Agricultural ET in millimeters for southern Idaho developed from Landsat TM data. ET is seasonal (March 15, 2000 to October 15, 2000)

## Applications in the Imperial Valley

Evapotranspiration maps have been created using METRIC and Landsat 7 images for much of Imperial Valley, California, for the January-March periods of 2002 and 2003 (Allen et al., 2003). The application demonstrated the ability to produce maps of quantitative, spatial distribution of monthly ET in near real time with resolution on the sub-field scale. The high resolution maps from Landsat were also useful in comparing ET in the "lower" ends of surface irrigated fields with ET in the "higher" ends of fields. Often, ET in lower ends of surface irrigated fields can suffer due to low irrigation uniformity or effects of salinity and inadequate leaching of salts.

## Applications in the Middle Rio Grande

METRIC was applied with Landsat 5 and 7 images to irrigated and riparian areas along the Middle Rio Grande river of northern and central New Mexico for year 2002, to spatially and temporally quantify ET by irrigated crops and by riparian vegetation (native and invasive tree species and wetlands) (Allen et al., 2004). The high resolution of Landsat was, again, extremely valuable for assessing ET on a field by field basis and for estimating ET from riparian (tree) systems that were often less than 100 m in width. The Landsat based ET maps, derived for each month of the year, were valuable in showing the amount of evaporation from abandoned agricultural fields that had high water tables. The high water tables precluded farming operations and supplied water to the surface for evaporation. Reducing these evaporation losses by lowering water tables would constitute a real conservation of water in the valley.

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